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RESEARCH MEMORANDUM

A FLIGHT INVESTIGATION OF SOME EFFECTS OF AUTOMATIC CONTROL ON GUST LOADS

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

A series of flight tests with a transport airplane were made to determine the effects of automatic control on loads in flights through clear rough air. The effects of increased autopilot sensitivity on the loads were also investigated. The test results indicate that the loads experienced by the test airplane when automatically controlled were consistently less than those without automatic control. The magnitude of the difference between the loads with and without automatic control was roughly 7 percent. There was no apparent change in the effect of the autopilot on gust loads for a small increase in autopilot sensitivity.

INTRODUCTION

The present trend toward automatic control of airplanes has created a need for information on the effects of automatic control on loads developed in flight through rough air. Some theoretical studies of this problem have been made (refs. 1 and 2), but little experimental information is currently available. The present paper describes some flight test results obtained with a transport airplane on the effects of automatic control on loads in flight through rough air.

The flight test data presented herein were obtained from a cooperative investigation by the National Advisory Committee for Aeronautics and the Directorate of Flight and All-Weather Testing of the U. S. Air Force at Wright-Patterson Air Force Base, Ohio. The test consisted of a limited series of systematic flights in clear rough air with an automatic pilot alternatively on and off. Comparison of the loads experienced with and without automatic control provided a measure of the over-all effects of automatic control on gust loads. In addition, the effects of increased autopilot sensitivity on gust loads were investigated.

APPARATUS

A three-view drawing of the airplane used in the investigation is shown in figure 1. The test airplane was equipped with a U. S. Air Force E-4 autopilot with rate control. A block diagram of the airplane-autopilot combination is shown in figure 2. The characteristics of the airplane as flown were as follows:

Mean aerodynamic chord, ft	9.72
Wing area, sq ft	817
Span, ft	91.75
Aspect ratio	10
Slope of lift curve per radian	5.0
Wing loading, lb/sq ft	44.0
Average test weight, lb	36,000
Static margin, $dC_{m_{cg}}/dC_L$	-0.16
Average center-of-gravity position, percent M.A.C.	23

The instruments installed in the test airplanes to obtain measurements pertinent to gust loads and the characteristics of the instruments are as follows:

Airspeed recorder:
- Range, mph . . . . . 0 to 300

Altitude recorder:
- Range, ft . . . . . 0 to 40,000

Recording accelerometer at center of gravity:
- Range of normal acceleration, g-units . . . . . 2 to -1
- Sensitivity, in./g 2
- Frequency, cps 9.25
- Damping, percent of critical 70

Control position recorders:
- For elevator:
  - Range, deg . . . . . ±10
  - Sensitivity, deg/in. 10
  - Frequency, cps 13.3
- For aileron:
  - Range, deg . . . . . ±10
  - Sensitivity, deg/in. 15
  - Frequency, cps 13.3
- For rudder:
  - Range, deg . . . . . ±10
  - Sensitivity, deg/in. 9.5
  - Frequency, cps 14.2

Turnmeters:
  For pitch:
    Range, radians/sec . . . . ±0.25
  For roll:
    Range, radians/sec . . . . ±0.25
  For yaw:
    Range, radians/sec . . . . ±0.25

METHODS AND TESTS

The test method consisted of comparing the loads measured on the airplane with and without automatic control in flights through clear-air turbulence. Since the runs made without automatic control were to be used as a reference to measure the effect of the autopilot on gust loads, it was necessary that the influence of the pilot on the results be minimized. The pilot was instructed, therefore, to use the controls only when it was necessary to correct for any large variations from the proper altitude and airspeed and then the control movements were to be made as slowly as possible.

The flight test procedure consisted of flying the test airplane through clear-air turbulence over a given course approximately 22 miles long at an indicated airspeed of 300 ft/sec and a pressure altitude of 2,500 feet (1,500 feet above the terrain). A total of nine flights were made during the test, each flight consisting of successive runs over the course with the airplane without automatic control, automatically controlled without altitude control, and automatically controlled with altitude control. The turbulence level was consistent over the small length of time involved in making any one flight. The number of runs for each individual flight varied according to the flight time available. However, at least two runs were made at each of the three control conditions in any one flight.

The automatic pilot was adjusted and calibrated according to CAA standards (normal sensitivity) and was flown in this configuration for the first seven flights. For the two remaining flights, the autopilot sensitivity was increased approximately 17 percent for the elevator displacement and 40 percent for the aileron displacement (see the appendix).

EVALUATION AND RESULTS

The acceleration records for each run were evaluated to obtain the magnitude of the maximum acceleration between any two consecutive intersections of the record line and the 1g reference. The evaluation was confined to values of acceleration increments of 0.15g or higher. Since there were minor changes in weight and airspeed during the flight tests, the acceleration data were adjusted to a standard wing loading of 44.0 lb/sq ft and an airspeed of 300 ft/sec on the basis that the acceleration is inversely proportional to the airplane weight and directly proportional to the airspeed. The airspeed-altitude records were evaluated to obtain the average airspeed and altitude for each run from which the flight distance in air miles was computed for each run.

Since two autopilot sensitivities were used in the test and the turbulence level varied between flights, it was found convenient to separate the data according to the following three phases: (1) light turbulence and normal autopilot sensitivity, (2) moderate turbulence and normal autopilot sensitivity, and (3) moderate turbulence and increased autopilot sensitivity. Each phase consisted of several test runs at each of the three control conditions of autopilot off, autopilot on and altitude control off, and autopilot on and altitude control on. The corrected acceleration data of each control condition were sorted into class intervals of 0.05g and are presented in the form of frequency distributions for each test phase in tables I(a), (b), and (c). These tables also show the total miles of flight for each control condition. The frequency distributions were used to obtain the average flight miles $\overline{M}(\Delta n)$ required to equal or exceed given values of acceleration increments for each control condition by means of the following relation:

$$\overline{M}(\Delta n) = \frac{M}{N(\Delta n)}$$

where

M total miles flown for a given control condition

$N(\Delta n)$ number of accelerations equal to or greater than a given increment for the corresponding control condition

The results obtained in this manner from the frequency distribution of each control condition of the three test phases are shown in terms of the average miles to equal or exceed a given acceleration increment in figures 3(a), (b), and (c).

Inasmuch as the data represented limited samples and the observed differences in acceleration experience between the autopilot on and off conditions were in general small (see figs. 3(a), (b), and (c)), a statistical analysis was necessary in order to insure that the observed differences represented real effects and not chance fluctuations. The following procedure, which is essentially an adaptation of standard statistical techniques to the present data, was used in evaluating the significance of the differences observed:

(1) For individual pairs of runs with and without automatic control, the load ratio given by $\dfrac{\Delta n(\text{with automatic control})}{\Delta n(\text{without automatic control})}$ was determined for a given flight distance.

(2) Each value of this load ratio was then considered to be an independent measure of the effectiveness of the automatic pilot in reducing loads. The mean value, the standard deviation of the individual values, and the standard deviation of the mean were determined by the method of reference 3 (pp. 64 and 65) for the load ratios for all the test data combined and for each of the test phases.

(3) The standard deviations were used in accordance with the methods of reference 3 (pp. 144 and 145) to obtain 95-percent confidence limits for the mean values of the load ratio. Confidence limits determined in this manner have a 95-percent probability of enclosing the true value and provide a measure of the reliability of the observed differences in loads between the runs with and without automatic control.

The average flight distance used for the determination of the load ratios was 4 miles since this value seemed to lie within the range where the data were most reliable. Other values of flight distance were tested and yielded similar results. Since the results without altitude control differed very little from those with altitude control, the statistical results are shown for only the test data with the altitude control off. Figure 4 shows the mean values of the load ratios and the 95-percent confidence limits for all the flight data and for each of the three test phases separately.

DISCUSSION

Consideration of the results in figures 3(a), (b), and (c) indicates that, for the ranges of turbulence severity and autopilot sensitivity studied, the loads experienced by the test airplane when automatically controlled were consistently less than those experienced without automatic control. These figures also show that the loads of the automatically controlled runs with altitude control differed very little from those without altitude control.

The results of the analysis to determine the significance of the differences in loads with and without automatic control (fig. 4) show that there is 95-percent probability that the load ratio for the over-all data lies within the range from 0.89 to 0.97. It therefore appears that a significant reduction in gust loads, roughly 7 percent as shown by the mean value, is achieved by the use of automatic control. Further examination of figure 4 shows that the confidence limits of the individual test phases are somewhat wider than those for the over-all data because of the smaller samples involved. There is, however, close agreement between the load ratios for the three test phases; this agreement indicates that the effects of automatic control on gust loads are largely independent of the turbulence severity or the autopilot sensitivity over the ranges studied.

Examination of the data disclosed an unusual effect in that the data obtained without automatic control under the moderate turbulence conditions (phases 2 and 3) showed a tendency for consistent variation in load experience with the flight heading relative to the prevailing wind. For the three flights involved, the wind velocities ranged from 30 to 55 mph and the predominant wind direction was parallel to the flight path. The loads experienced for the down-wind runs in these data appeared to be roughly 10 to 15 percent larger than the loads obtained for the up-wind runs. Although the reason for this variation could not be determined and might well be due to chance because of the small size of the sample data, it might also be a reflection of variations in piloting technique in flying up and down wind at low altitudes.

CONCLUSIONS

On the basis of the results of a limited flight investigation with a transport airplane to determine the effects of automatic control on gust loads it was concluded that, over the range of turbulence severity studied:

1. The loads experienced by the test airplane when automatically controlled were consistently less than those without automatic control. The magnitude of the difference between the loads with and without automatic control was roughly 7 percent.

2. There was no apparent change in the effects of the autopilot on gust loads for a small increase in autopilot sensitivity.

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APPENDIX

DETERMINATION OF THE DIFFERENCE IN THE TWO AUTOPILOT SENSITIVITIES

Since two different autopilot settings were used in this investigation, it was necessary to determine the relative sensitivities of the two settings by flight tests. For the first sensitivity, the autopilot was adjusted and calibrated according to CAA standards. For the second sensitivity, the elevator and aileron displacement settings were changed to give the maximum ratio of control displacement to the airplane displacement in pitch and roll. Further increase in the control displacement gave an unstable oscillation of the controls.

The relative sensitivities were determined by using the following procedure for both autopilot settings:

The airplane was trimmed for straight and level flight and the autopilot engaged. The pilot then overpowered the autopilot to place the airplane in a 10° nose-up attitude and, when steady conditions were obtained, the controls were released and the autopilot was allowed to return the airplane to its original attitude. By measuring the maximum elevator deflection obtained after the pilot released the controls, the relative sensitivity in pitch was determined for the two autopilot settings. The relative sensitivity in roll was determined by the same method except that the aileron deflections for the recovery of the airplane from a steady 30° banking turn were used.

Figure 5 shows representative time histories of the elevator movements, airspeed variation, and pitching velocity after the pilot released the controls in a pull-up and hold maneuver. The control deflections are measured from the position of the controls at the time they were released by the pilot. Measurements of the control movements from several records such as those in figure 5 indicated that the elevator displacement was increased approximately 17 percent for the increased sensitivity and the aileron displacement was increased approximately 40 percent.

REFERENCES

1. Rhoads, Donald W.: Calculated Short Period and Phugoid Responses of an F-80A Airplane to Vertical and Horizontal Sharp-Edged Gusts, Including Automatic Control. Rep. No. TB-785-F-1, Cornell Aero. Lab., Inc., Nov. 1, 1951.

2. Neumark, S.: The Disturbed Longitudinal Motion of an Uncontrolled Aircraft and of an Aircraft With Automatic Control. R. & M. No. 2078, British A.R.C., 1943.

3. Hoel, Paul G.: Introduction to Mathematical Statistics. John Wiley & Sons, Inc., 1947.

TABLE I.- FREQUENCY DISTRIBUTION OF ACCELERATION

(a) Phase 1 - Light turbulence and normal autopilot sensitivity

Class interval, Δn, g	Number of acceleration increments		
	Automatic control off	Automatic control on and altitude control off	Automatic control on and altitude control on
0.15 to 0.20	600	521	512
.20 to .25	208	183	174
.25 to .30	95	64	49
.30 to .35	29	22	18
.35 to .40	8	7	8
.40 to .45	2	2	2
.45 to .50	0	0	
.50 to .55	0	0	
.55 to .60	0	1	
.60 to .65	1		
Total flight miles	372	370	369

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TABLE I.- FREQUENCY DISTRIBUTION OF ACCELERATION - Continued

(b) Phase 2 - Moderate turbulence and normal autopilot sensitivity

Class interval, Δn, g	Number of acceleration increments		
	Automatic control off	Automatic control on and altitude control off	Automatic control on and altitude control on
0.15 to 0.20	554	654	503
.20 to .25	350	402	310
.25 to .30	249	223	150
.30 to .35	151	111	94
.35 to .40	71	53	53
.40 to .45	51	32	22
.45 to .50	22	18	15
.50 to .55	18	12	9
.55 to .60	14	6	8
.60 to .65	7	1	1
.65 to .70	3	3	2
.70 to .75	1	1	1
.75 to .80	2		0
.80 to .85	2		1
.85 to .90	0		1
.90 to .95	0		1
.95 to 1.00	1		
Total flight miles	133	135	127

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TABLE I.- FREQUENCY DISTRIBUTION OF ACCELERATION - Concluded

(c) Phase 3 - Moderate turbulence and increased autopilot sensitivity

Class interval, Δn, g	Number of acceleration increments		
	Automatic control off	Automatic control on and altitude control off	Automatic control on and altitude control on
0.15 to 0.20	891	891	870
.20 to .25	474	395	476
.25 to .30	252	194	234
.30 to .35	108	76	89
.35 to .40	52	30	38
.40 to .45	22	13	22
.45 to .50	14	3	7
.50 to .55	6	4	4
.55 to .60	3	0	0
.60 to .65	2	1	2
.65 to .70		1	0
.70 to .75			0
.75 to .80			0
.80 to .85			0
.85 to .90			1
Total flight miles	252	256	256

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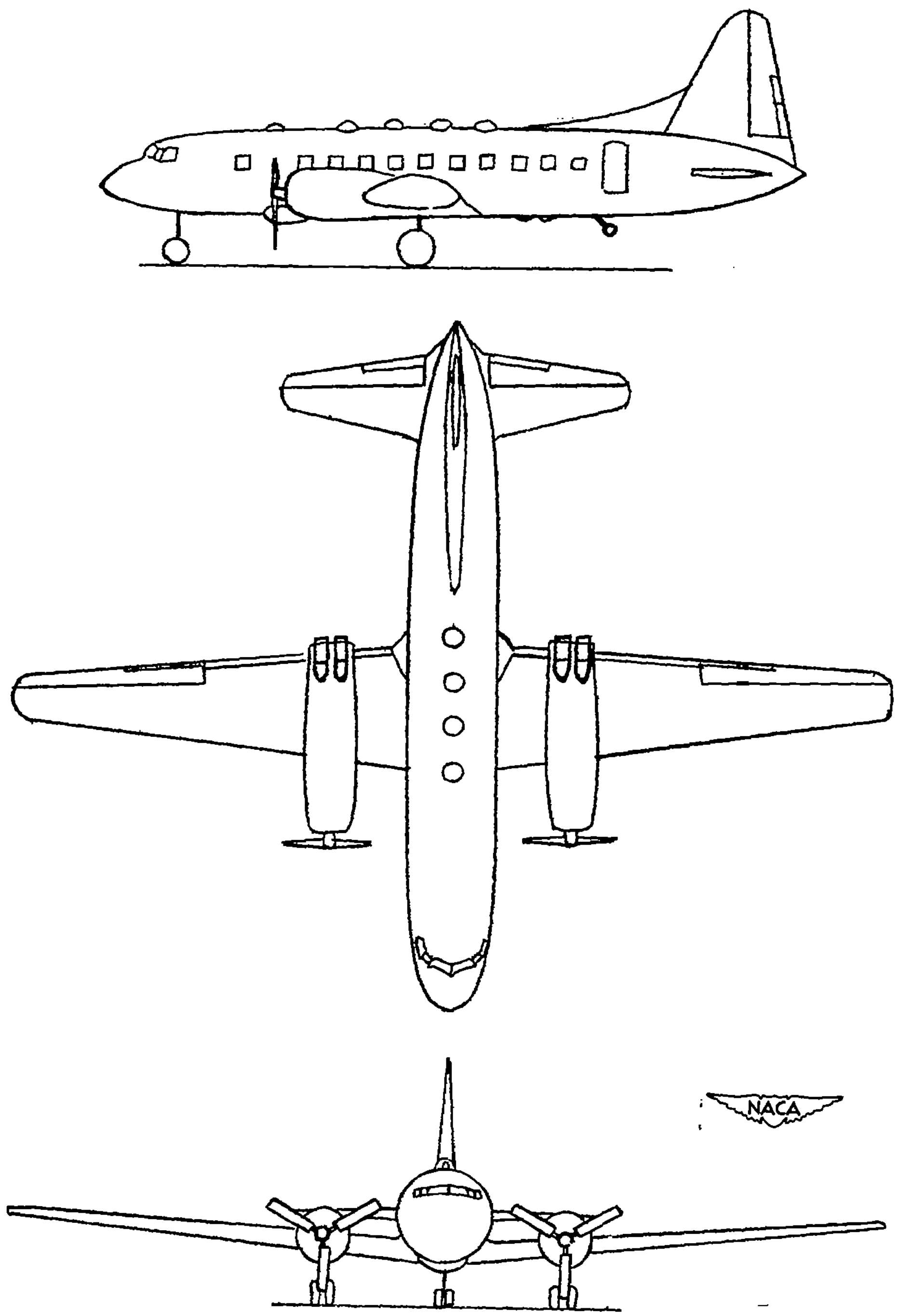


Figure 1.- Three-view drawing of the test airplane.

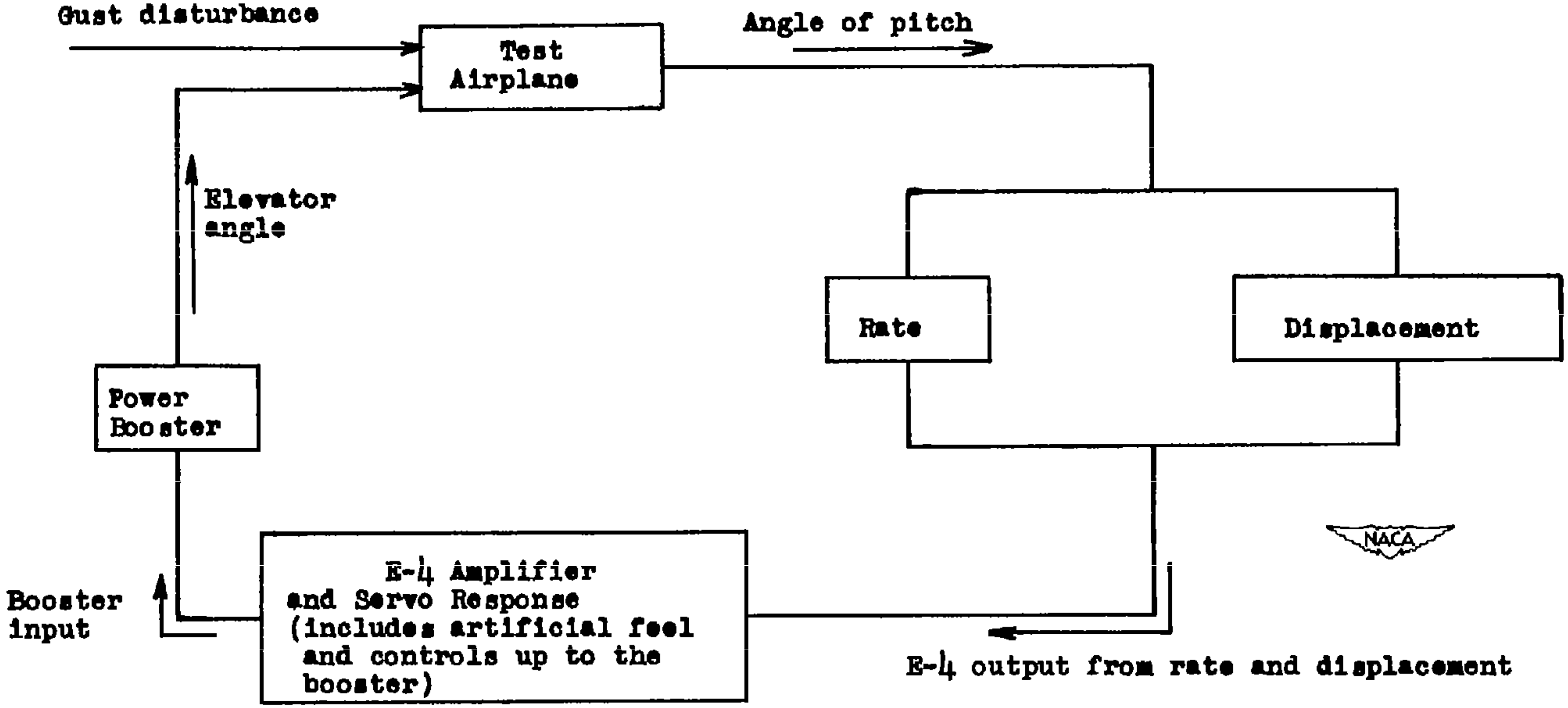
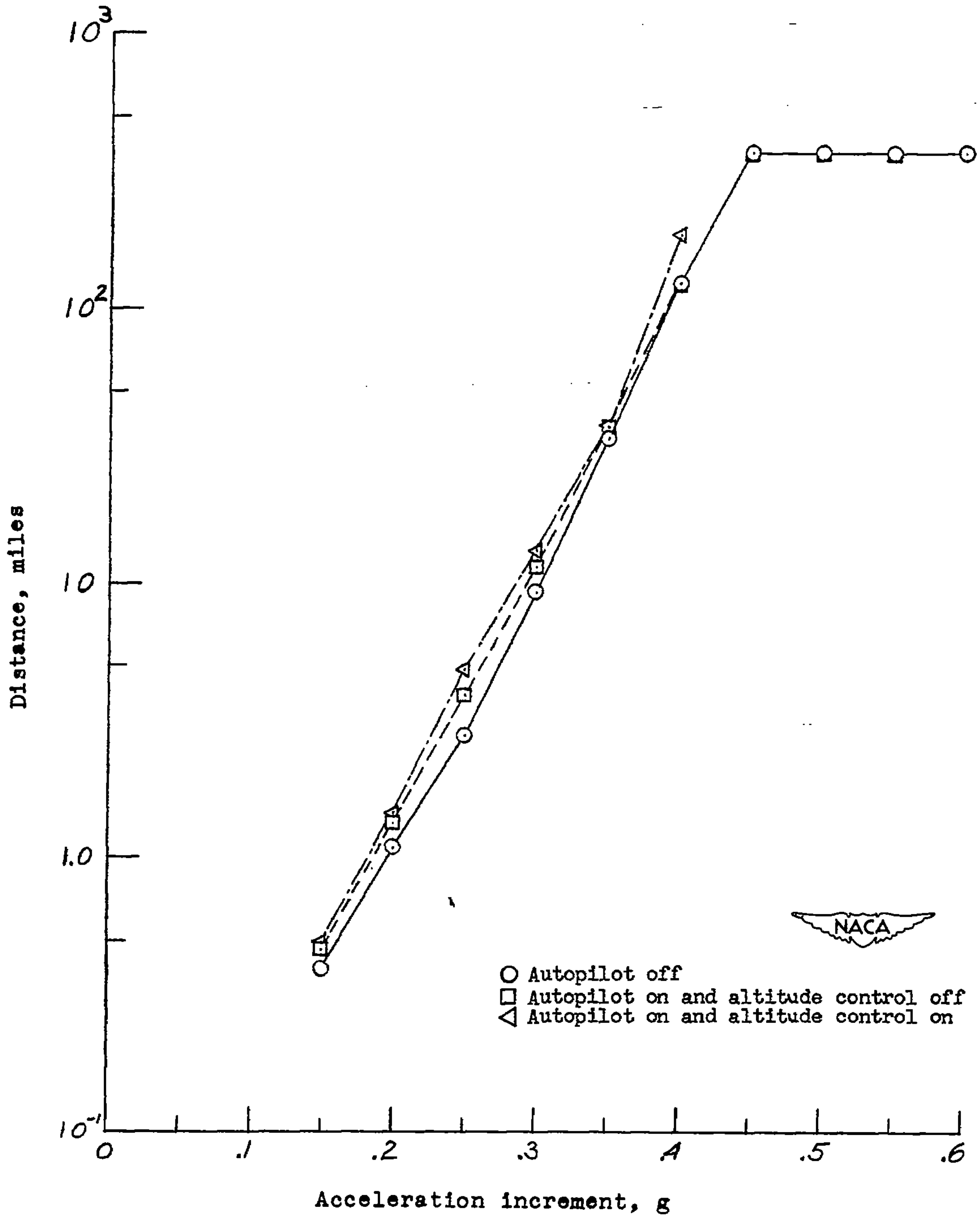
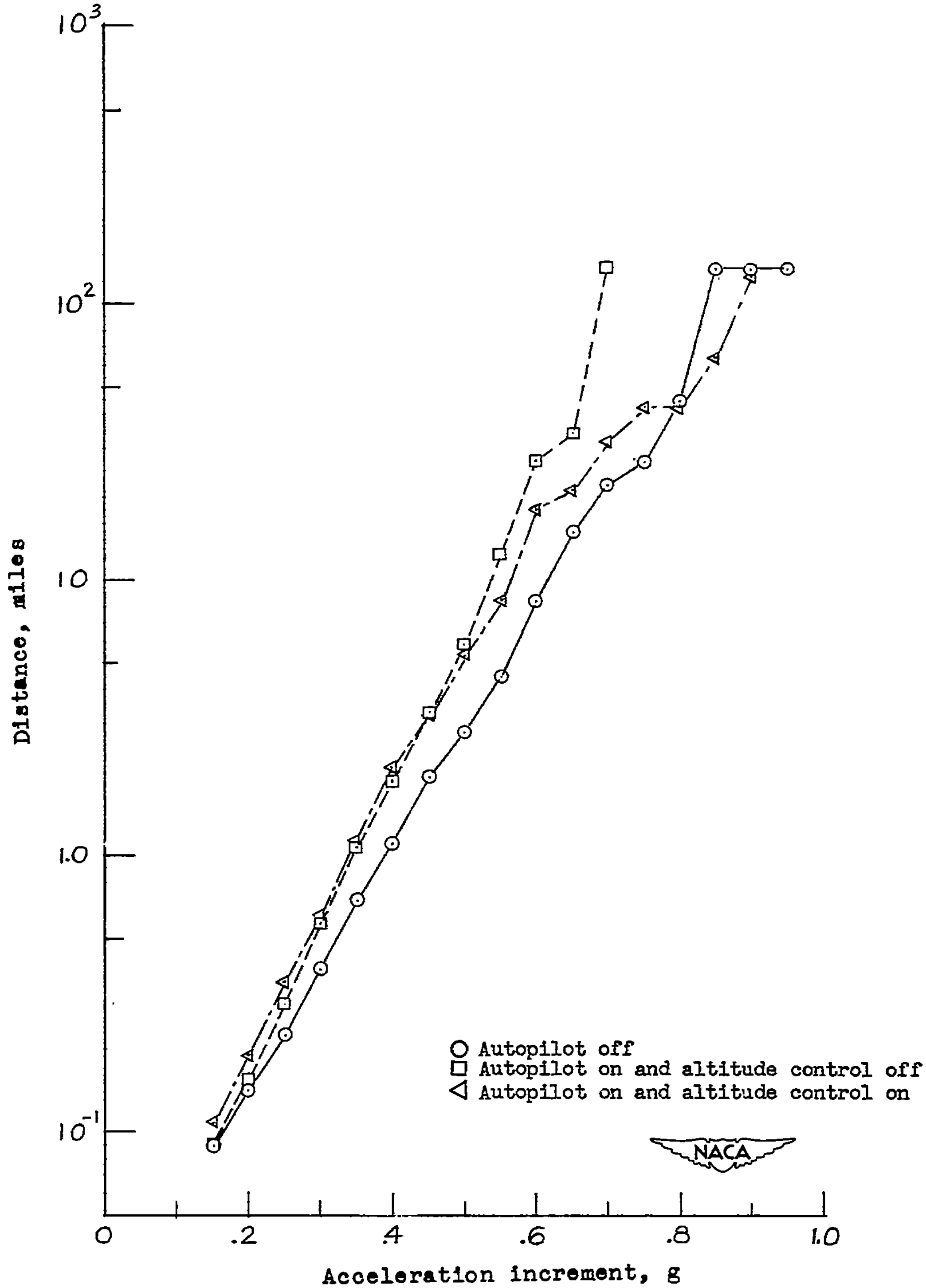


Figure 2.- A block diagram of the test airplane and U. S. Air Force E-4 autopilot system.



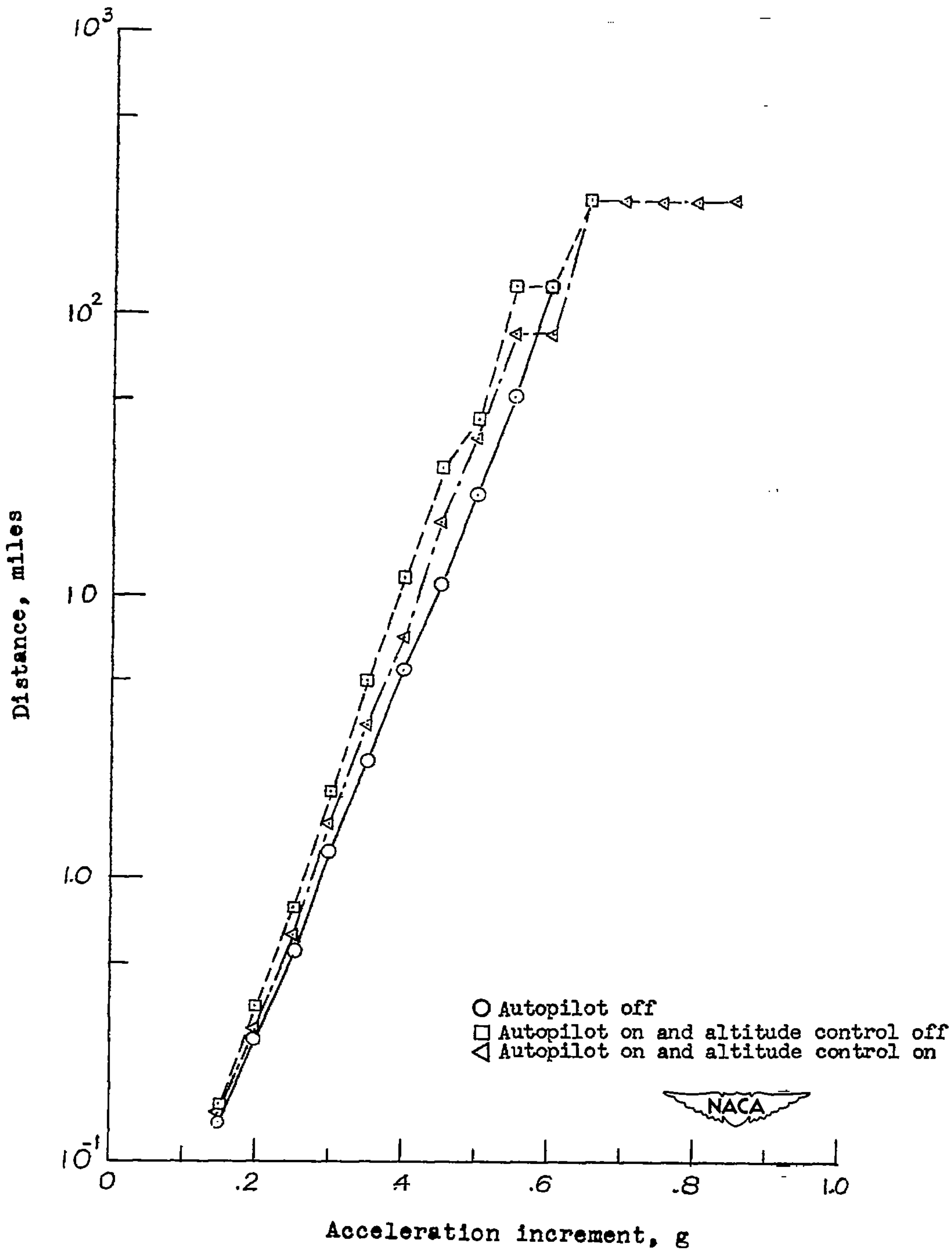
(a) Phase 1 - Light turbulence and normal autopilot sensitivity.

Figure 3.- The average number of miles flown to exceed a given acceleration increment.



(b) Phase 2 - Moderate turbulence and normal autopilot sensitivity.

Figure 3.- Continued.



(c) Phase 3 - Moderate turbulence and increased autopilot sensitivity.

Figure 3.- Concluded.

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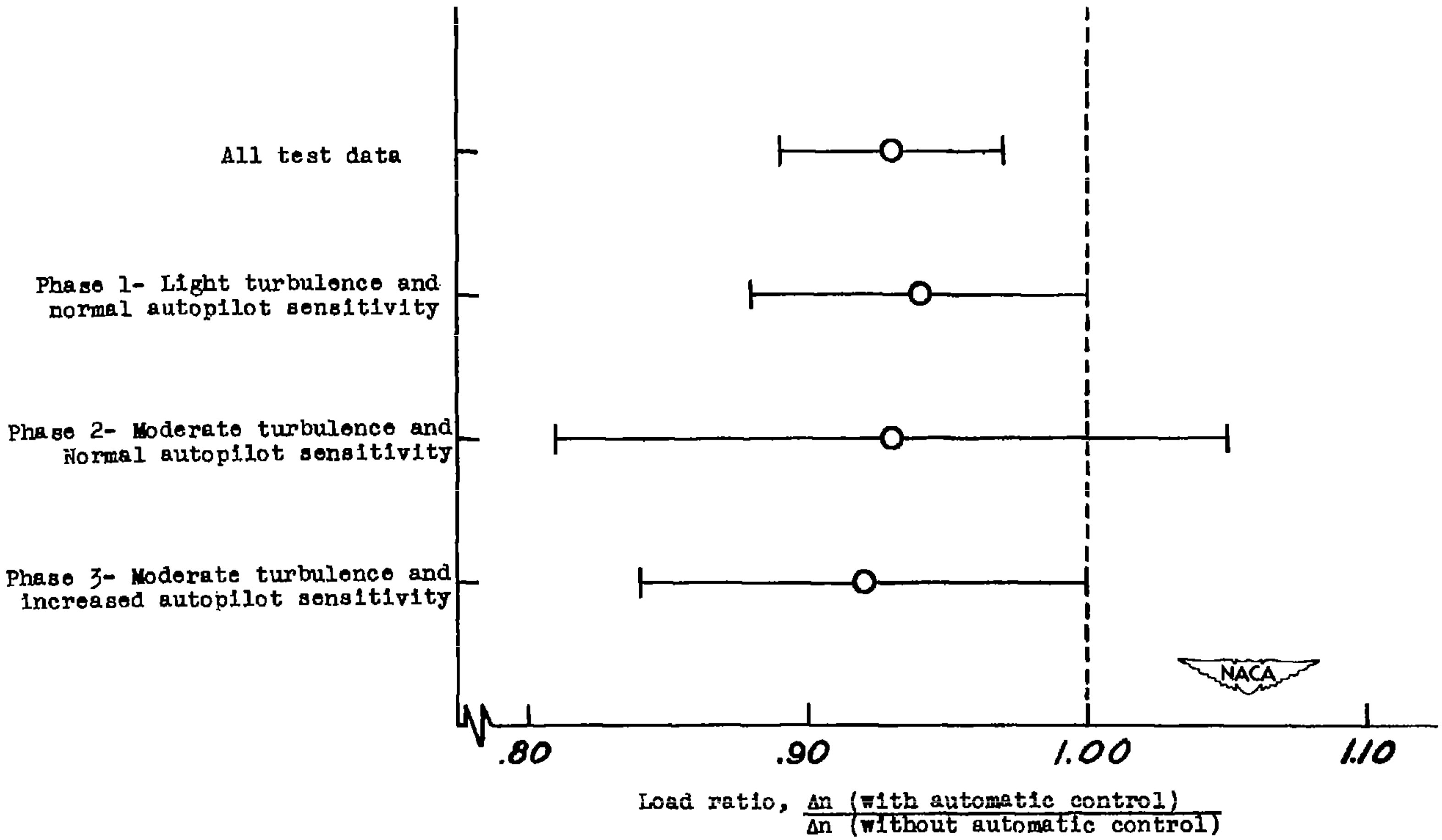

Figure 4.- The mean ratios of the loads with automatic control to the loads without automatic control and the corresponding 95-percent confidence limits.

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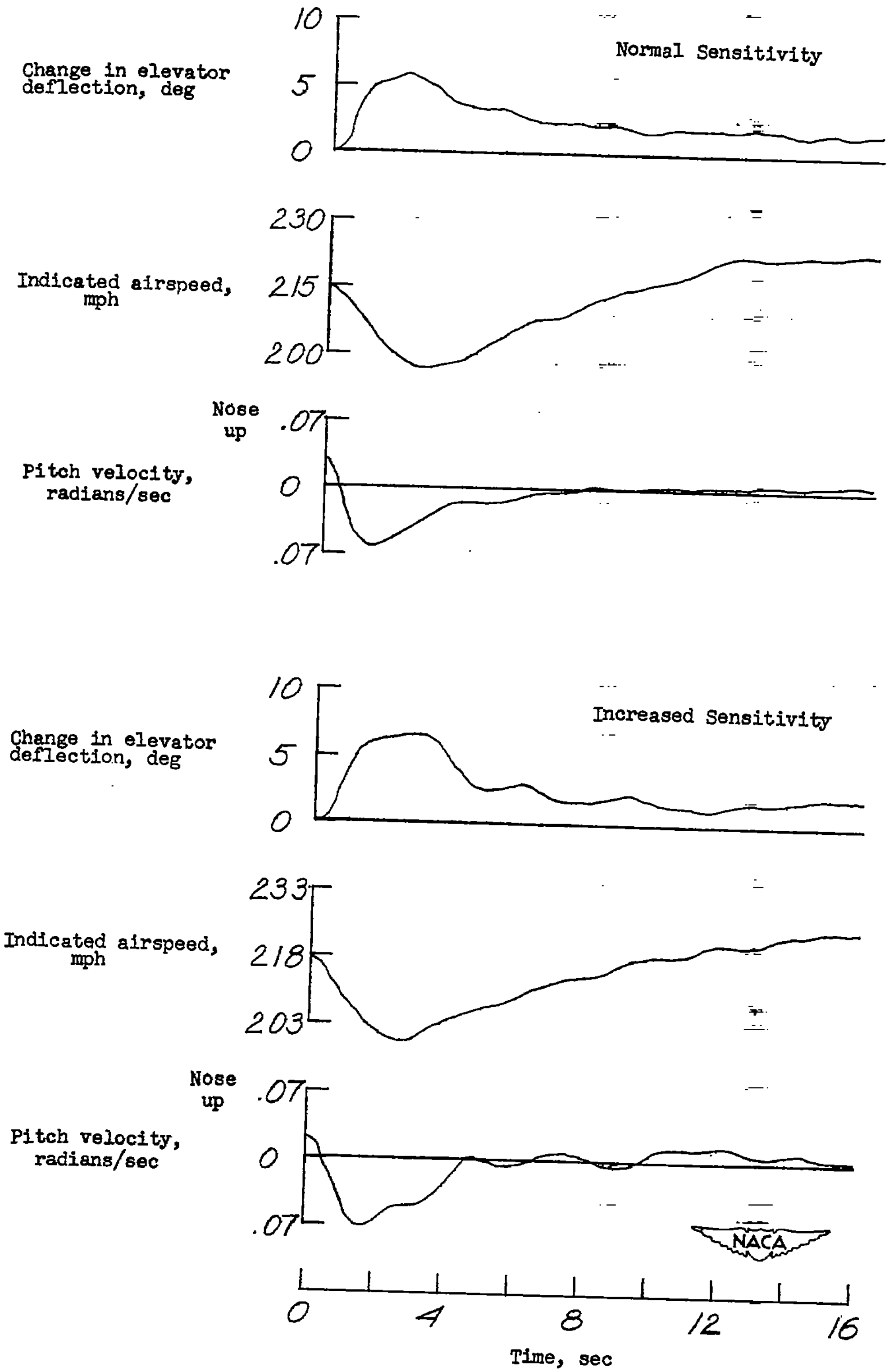

Figure 5.- Time histories of the elevator movements, airspeed variation, and pitching velocity for the recovery from a 10° nose-up attitude.

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